Strong Magnetic Field Generated by the Extreme Oxygen-rich Red Supergiant VY Canis Majoris

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Evolved stars experience high mass-loss rates forming thick circumstellar envelopes (CSEs). The circumstellar material is made of the result of stellar nucleosynthesis and, as such, plays a crucial role in the chemical evolution of galaxies and the universe. Since asymmetric geometries of CSEs are common, and with very complex structures for some cases, radiative pressure from the stars can explain only a small portion of the mass-loss processes; thus the essential driving mechanism is still unknown, particularly for high-mass stars. Here we report on magnetic field measurements associated with the well-known extreme red supergiant (RSG), VY Canis Majoris (VY CMa). We measured the linear polarization and the Zeeman splitting of the SiO $v=0$, $J=1$–0 transition, using a sensitive radio interferometer. The measured magnetic field strengths are surprisingly high; their upper limits range between 150 and 650 Gauss within 530 AU (~80 R_*) of the star. The field strength of lower limit is expected to be at least ~10 Gauss based on the high degree of linear polarization. Since the field strengths are very high, the magnetic field must be a key element in understanding the stellar evolution of VY CMa as well as the dynamical and chemical evolution of the complex CSE of the star. M-type supergiants, with large stellar surface, were thought to be very slow rotators. This would seem to make a dynamo in operation difficult and would also dilute any fossil magnetic field. At least for VY CMa, we expect that powerful dynamo processes must still be active to generate the intense magnetic field [1].

The CSE of VY CMa has exceptionally strong SiO lines - most of them are masers - in many rotational transitions in multiple vibrational states, along with strong H_2O maser emission [2], over a wide range of energy levels, up to ~7,000 K for SiO and ~7,800 K for H_2O. Furthermore, many SiO lines associated with the CSE are highly polarized, both in circular [3] and linear polarization ([1] and references therein), from a few percent up to $\gtrsim 60\,\%$ in linear polarization. This high degree of polarization is even detected in low rotational transitions in the ground vibrational state [4], which is usually of thermal origin, as the $v=0$, $J=1$–0 and 2 energy levels are only 2 K and 6 K above ground, respectively.

Zeeman effect in SiO $v=0$, $J=1$–0 emission was detected for the first time from an astronomical object. Along with well-ordered magnetic field pattern measured with high degree of linear polarization, the observational results presented here strongly indicates that this enigmatic O-rich RSG VY CMa has a very intense magnetic field of from 10 Gauss up to 150–650 Gauss. Future observations will further constrain the magnetic field strengths to understand the physics of high mass-loss rate and the stellar evolution of high-mass stars just before supernova explosion.

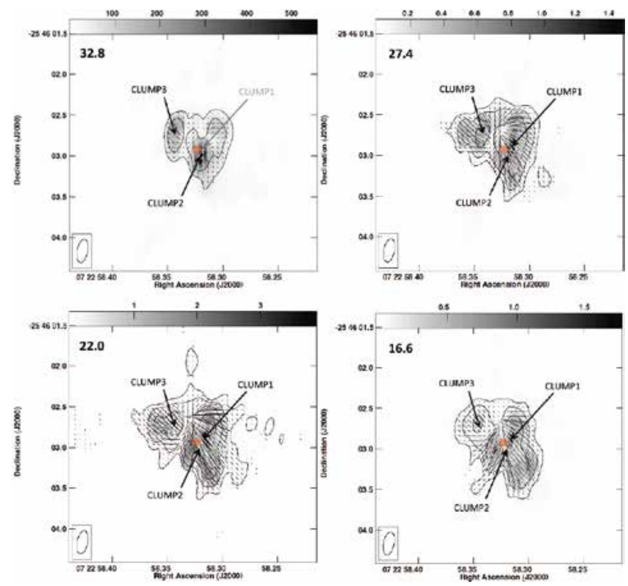

Figure 1: Channel maps of SiO $v=0$, $J=1$–0 emission (contours drawn at (9, 27, 81, 243, 729) times of 1σ noise level of 6.8×10^{-3} Jy/beam; 0."29 x 0."12 beam size) with polarization vectors (black/white bars) measured with the VLA. $V_{\rm lsr}$ is written on the top left corner of each panel. The polarized intensity unit (grey scale) of the top left panel and that of the rest panels are in mJy/beam and in Jy/beam, respectively. Polarization vectors are plotted when the signal-to-noise ratio for intensity is above 8 sigma. Each clump and the stellar location ([2]; orange circle, measured with ALMA) are noted.

References

[1] Shinnaga, H., et al.: 2017, *PASJ*, **69**, L10.
[2] Richards, A. M. S., et al. 2014, *A&Ap*, **572**, L9.
[3] Barvainis, R., McIntosh, G., Predmore, C. R.: 1987, *Nature*, **329**, 613.
[4] Shinnaga, H., Tsuboi, M., Kasuga, T.: 1999, *PASJ*, **51**, 175.